Green Energy and Technology

Luis Baringo
Miguel Carrión
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Electric Vehicles and Renewable Generation

Power System Operation and Planning Under Uncertainty

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Green Energy and Technology

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To Carmen, María, and Luis
To Sofía and Mayte
To Felipa, Jesús, Doroteo, and Maruja

Preface

Power systems are experiencing relevant changes that are modifying their structures, participants, and functioning procedures. The ever-increasing installation of renewable generation technologies, which most of them are characterized by uncertain and variable power outputs, is changing the traditional generation mixes of power systems, typically composed of thermal and hydropower units. Additionally, the continuous electrification of energetic processes, such as heating and transportation sectors, may change significantly the demand profiles in the future. In particular, the foreseen massive replacement of combustion-engine vehicles by electric vehicles is expected to cause different operational problems due to possible high peak consumption at specific time periods. Consequently, new tools are required to assist in the operation of current and future power systems. Moreover, planning models considering these aspects are also needed to gather a technical and economical proper transition from current power systems to future ones.

This book provides a set of operation and planning models for power systems that explicitly take into account the presence of a large capacity of renewable generation technologies and a high number of electric vehicles. Then, innovative short- and long-term decision-making models are comprehensively described considering the points of view of power system operators, planners, and aggregators of electric vehicles. The presented models take into account different sources of uncertainty, which are handled using different mathematical tools.

This book comprises twelve chapters. Chapters 1–3 describe the situation of current and future power systems, as well as the models and tools that are used throughout the book. Chapters 4 and 5 provide short-term decision-making tools taking the perspective of the power system operator. Chapters 6 and 7 face problems dealt by electric vehicle aggregators and energy suppliers, respectively. Chapters 8–12 describe planning models. Chapters 8–10 are devoted to the determination of the generation and storage capacity investments, whereas Chaps. 11 and 12 take the points of view of transmission and distribution network planners, respectively. The contents of this book are summarized below.

Chapter 1 describes briefly the operating and planning problems that power system operators and participants will face in future power systems. The main challenges of future power systems are also described in this chapter, focusing on the role that renewable energies and electric vehicles are expected to play. Finally, some motivating examples are described.

Chapter 2 presents relevant modeling information about the operation of power systems. It also describes the energy production process of wind and solar photovoltaic power plants and the modeling of the energy consumption of electric vehicles. Additionally, this chapter analyzes the temporal characterization of long-term planning horizons.

Chapter 3 provides the fundamentals of some mathematical tools that are used throughout this book. The basics of stochastic programming and robust optimization are presented. The practical implementation of the linear decision rules approach and the Benders' decomposition technique are described in detail.

Chapter 4 models the day-ahead energy and reserve scheduling of a renewable-dominated power system considering the uncertainty in the balancing market. The presented model is based on stochastic programming and adopts the perspective of the system operator. The uncertainty of the hourly demand, and wind and solar power is modeled through a set of scenarios.

Chapter 5 studies the day-ahead scheduling problem of a power system with a high presence of electric vehicles. The presented model considers that electric vehicles can provide reserve services when they are connected to the grid. The system demand, the intermittent renewable power, and the battery status of electric vehicles are considered uncertain parameters. This model is formulated as a stochastic programming problem.

Chapter 6 analyzes the bidding strategy problem of an aggregator of electric vehicles. Different models are presented in this chapter that take into account the uncertainty in market prices and driving needs. The impact of the bidding decisions of the electric vehicle aggregator on market prices is also addressed in the decision-making tool.

Chapter 7 describes the selling price determination problem faced by an electricity supplier that provides the energy demand of a set of electric vehicle users. The presented procedure considers the uncertainty of the electricity prices, the consumption patterns of electric vehicles, and the selling prices offered by rival suppliers.

Chapter 8 presents the static generation expansion planning problem of a power system considering renewable energies. This problem is modeled taking the perspective of a central planner that aims at determining the generation expansion plans that minimize both the investment and operation costs. Short- and long-term uncertainties are modeled using both scenarios and confidence bounds, which allows formulating this problem using stochastic programming and robust optimization approaches, respectively.

Chapter 9 extends the model presented in Chap. 8 considering that investment decisions can be made at different stages along the planning horizon. The demand growth and the investment costs of the units are considered uncertain parameters.

The presented model is formulated using both stochastic programming and linear decision rules approaches.

Chapter 10 describes the generation expansion problem considering explicitly the presence of electric vehicles. The presented model assumes that electric vehicle users may be willing to leave the charge of their vehicles in hands of the power system operator if high-enough financial incentives are offered to them. The model analyzed in this chapter considers uncertainties such as the annual demand growth, the capital costs of generating and storage units, and the number of electric vehicles. The proposed model is formulated using a two-stage stochastic programming problem.

Chapter 11 analyzes the transmission expansion problem considering the presence of renewable energies and electric vehicles. The presented model determines the transmission lines to reinforce and the storage facilities to install. A two-stage stochastic programming formulation is proposed considering the uncertainties of the generation capacity installed and the number of electric vehicles.

Chapter 12 studies the distribution expansion problem considering a large number of chargers for electric vehicles. The presence of electric vehicle chargers may change substantially the energy load at some locations and may require the reinforcement of the distribution system to preserve its adequate operation. A non-linear programming formulation is proposed to determine the reinforcement of the distribution grid.

This book is intended to be useful for energy engineering and economics communities. In particular, graduate students and practitioners may profit from the different models proposed in this book. The large number of illustrative examples included throughout each chapter, as well as the analyzed illustrative and realistic case studies, intend to facilitate the comprehension of the theoretical concepts included in this book.

Many colleagues have contributed with their views, comments, and research to inspire the contents of this book. We are grateful to Prof. Conejo from the Ohio State University; Prof. Oggioni from the University of Brescia; Profs. Morales and Pineda from the University of Málaga; Prof. Pandžić from the University of Zagreb; Prof. Dvorkin from the Johns Hopkins University; Prof. Vitali from the University of Bergamo; Prof. Ruiz from the University Carlos III de Madrid; Profs. Alguacil-Conde, Arroyo, Cañas-Carretón, and García-Bertrand from the University of Castilla-La Mancha; and in particular, we would like to acknowledge the work of Prof. Zárate-Miñano from the University of Castilla-La Mancha that helped the authors to elaborate the contents of this book.

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Finally, we would like to state that the writing of this book has been really hard because of the difficult events that we all have experienced during years 2020 and

2021. However, we believe that the time and efforts we have dedicated in writing this book can be considered well spent if it contributes, only a little, to increase the interest of readers in the operation and planning of power systems.

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April 2022

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Part I
Introduction and Mathematical Characterization

Chapter 1
Introduction

This chapter provides an overview of the operation and planning problems that power system operators, planners, and participants will face in future power systems. The decision framework of each problem is also discussed. The main challenges of power systems are pointed out, focusing on the role of renewable energies and electric vehicles.

This chapter is organized as follows. Section 1.1 describes the main challenges that future power systems must face. Sections 1.2 and 1.3 describe the basic aspects of renewable energies and electric vehicles, respectively. Section 1.4 analyzes the presence of uncertainty in the different problems associated with the operation and planning of power systems. Section 1.5 outlines the different decision-making problems considered in this book and provides some motivating examples. Finally, Sect. 1.6 concludes this chapter providing a summary and some relevant remarks.

1.1 Challenges of Future Electricity Systems

Power systems have been continuously evolving since the first systems dedicated to the supply of electric light were developed at the end of the nineteenth century. However, we can observe that, nowadays, power systems are facing new challenges that call into question the procedures used to operate these systems so far.

The first challenge that power systems must handle is the fast incorporation of large capacities of new generation technologies, especially those based on wind and solar photovoltaic (PV) power. These technologies are based on renewable and weather-dependent sources that provide an intermittent power output. For this reason, the power plants belonging to these technologies are usually referred to as intermittent units. The installation of renewable technologies worldwide during the

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last decades has been massive and obeys to two main reasons. The first one is due to the increasing environmental concern of the societies. The desire to revert or reduce the consequences of the global warming by cutting off the emission of greenhouse gases (GHGs) has placed the focus of governments on the power sector, which is responsible of about one third of the global emissions of CO_2. In this sense, renewable technologies, which are characterized by very low GHG emissions during their life cycle, have been strongly promoted by governments to replace thermal units fed by fossil fuels, as coal and gas power plants.

The second reason that explains the rapid growth of the installation of renewable power plants is the technical development of these technologies and the strong reduction of their capital costs. The development of the power electronics at the end of the twentieth century increased the reliability and the capacity of power electronic devices and has boosted the installation of wind and solar PV technologies by private investors. Although the investments in renewable generating units required financial support by governments to ensure their profitability in the past, these technologies are currently economically competitive with respect to mature generation technologies and financial aids are not longer needed, specially for wind and solar PV technologies.

The performance of intermittent power plants is substantially different to that of traditional technologies, basically hydro and thermal power plants. As stated above, the production of intermittent plants is variable in time, but it should not be forgotten that this production is also uncertain. In other words, it is not possible to forecast with absolute precision the power output of an intermittent power plant in a future time period. These two characteristics, intermittency and uncertainty of the production, cause that 1 MW of a thermal power plant that is decommissioned from the system cannot be straightforwardly replaced by 1 MW of an intermittent generation technology. The variability and the uncertainty of the production of intermittent units, as well as the spatial correlation of the production of power plants located at different locations, must be carefully considered in the operation of an existing power system. Nonetheless, these issues should also be considered in the design process of new power systems, or in the transformation of existing power systems based on hydro and thermal generation technologies into new ones dominated by intermittent power plants.

Another important difference between the performance of conventional and intermittent power plants concerns the provision of inertia to the system. The inertia provided by the rotating elements of hydro, steam, or gas turbines is very useful to limit frequency variations produced by the imbalances between generation and consumption in a power system. Therefore, if an energy imbalance is produced, the excess or defect of energy can be partly or totally compensated by increasing or reducing the kinetic energy stored in the rotating elements of the turbines. However, the lack of turbines in solar PV plants or the existence of an electronic layer between the wind turbine and the network connection in wind power units prevents the provision of this inertia support. As a result, high frequency variations have been observed in systems with high penetration of intermittent units. To solve this problem, lots of efforts have been placed in the design and implementation of the provision of the so-called synthetic inertia by intermittent units. In this manner, the power output of intermittent units is adjusted electronically to counteract frequency variations. The results obtained from the provision of synthetic inertia in small power systems are promising. In the same vein, the presence of intermittent generation has an impact in the scheduling of ancillary services of the system. The ancillary services are a set of mechanisms that intend to balance the production and consumption at every moment maintaining grid stability and security. In this manner, higher amounts of reserve are scheduled when a large intermittent and uncertain generation is scheduled. However, nowadays, intermittent plants, specially wind power units, are also able to participate in the ancillary services to provide different types of reserves.

The economic impacts of the incorporation of intermittent units in the power systems are also non negligible. Unlike thermal units, and similarly to hydro units, intermittent units do not use fuel to produce energy and they are characterized by high investment costs but very low operation costs. However, contrary to those hydro units with water reservoirs that are able to decide in which periods they produce, intermittent units are able to produce energy only in those periods in which the renewable source is available. As a result, the operation of hydro and intermittent power units is essentially different. In this sense, given that water resources are limited, hydro units can decide to produce only in those periods in which electricity prices are high. On the other hand, considering that production costs of intermittent units are almost negligible and that the renewable resources as wind and solar irradiation cannot be stored in general, these technologies are interested in producing as long as the renewable resource is available.

The intermittent operation of most of renewable technologies has a high impact in the electricity prices of electricity markets, especially in the day-ahead market. The day-ahead market is typically the market in which most part of the electricity is traded by producers and consumers in a power system. This market is specially designed for the operation of hydro and thermal units and it schedules the production of each power plant one-day ahead in one-hour or half-hour basis. In this manner, thermal units can be configured to supply the scheduled power in each hour of the next day. Then, one-day ahead, producers submit generation offers stating for each hour of the next day the energy that they are willing to supply and the selling price for each offer. On the other hand, consumers (or electricity retailers) submit consumption bids with information about the energy that they are interested to buy and the purchasing price for each bid in every hour of the next day. Usually, the day-ahead market is settled using a marginal pricing mechanism that incentives producers to participate by offering selling prices equal to their operation costs. This market configuration is not beneficial for intermittent plants because it forces them to know the production of the plant one-day ahead. Since the accurate forecast of the renewable source of the intermittent plant is not possible, intermittent units are forced to be penalized for production deviations or to participate in adjustment markets to modify their production forecasts. The adjustment markets have an energy volume much lower than the day-ahead market and the participation in them is not always economically advantageous for intermittent power producers. Another consequence of the participation of intermittent technologies in the day-ahead market is the reduction of the electricity prices, which is good news for consumers but it can constitute a profitability problem for producers, including also intermittent power plants. Considering the marginal pricing used in most of day-ahead electricity markets, intermittent power plants are incentivized to offer prices close to zero that place out of the market those plants with higher operation costs. Then, if a large enough capacity of intermittent units participate in the day-ahead market, it is probable that electricity prices be close to zero in those periods in which the intermittent production be able to supply the system demand. Therefore, a cannibalism risk may exist if the amount of installed capacity of intermittent units is high enough to cause a decrease of prices avoiding the profitability of intermittent power plants. In order to avoid this situation, new trading platforms or remuneration mechanisms may be in order. For instance, the renewable auctions for installing new renewable plants that are used in many countries ensure economic incomes out of the market for new intermittent plants may be interesting to remunerate the production of these units. For these reasons, the adequate operation and planning of power systems dominated by intermittent power plants is currently an open research topic.

The second challenge that future power systems must face is the electrification of energetic processes that do not use electricity so far. It is expected that, in the incoming years, heating and low-temperature industry processes be electrified, as well as the transportation sector. The reason of the electrification of these processes is to decrease GHG emissions. The efficiency of electric engines is higher than that of thermal ones, and the emission of pollutants associated with electric devices may be low if the generation mix used to supply the demand of these vehicles is based on renewable energies. Consequently, the electrification of energetic processes is advised if GHG emissions are desired to be reduced.

The lead actor in this electrification process is the electric vehicle (EV). We can define an EV as a vehicle that is powered by electricity and is equipped with an electrochemical battery that can be charged from the grid. EVs are intended to replace combustion-engine vehicles progressively during the next decades. Governments around the globe have boosted decisively the usage of EVs for environmental and strategic reasons during the last years. From an environmental point of view, EVs are considered to be more efficient than combustion-engine vehicles since they do not emit pollutant gases and do not generate noise when they are driven. As stated above, the primary energy used to charge EVs may emit a low amount of GHGs if it is based on renewable energies. From an energy policy point of view, the increase of EVs may be useful to reduce the energetic dependence of some countries with respect to fossil fuels. This may be of special interest in those countries without fossil fuel reserves and with high potentials of renewable energies.

The massive integration of EVs is a challenge from several points of view. Although the increase of the annual system demand needed to charge the vehicles is technically affordable for most power systems, some problems may happen at some specific hours. For instance, cloudy days with low production of wind power may be problematic for renewable-dominated systems if the capacity of other generation technologies or storage units is not available. The ability of the system to ramp up and down the production in some specific hours has also to be adequate to face the simultaneous charge of a large number of EVs.

Notwithstanding the above, the main difficulties of the incorporation of EVs are expected at the distribution level. The charge of an EV may double the energy consumption of a home and triple the peak power demanded. Therefore, if a large number of EVs are simultaneously charged in a distribution network, voltage and distribution line congestion problems may happen. To avoid this situation, the reinforcement of the distribution system and smart charging procedures must be implemented to avoid the simultaneous charge of a high number of vehicles.

In this sense, demand-side management actions including the direct control of the charge of vehicles by an external entity may be advisable to reduce or delay the investments in new distribution assets. Observe that since vehicles are parked most of the time, EVs are ideal for participating in energy management actions. Additionally, they are equipped with a large battery that can be even discharged into the grid using vehicle-to-grid capabilities. Therefore, EVs can be used as energy storage units that can be useful to perform energy arbitrage and provide ancillary services to the grid. However, it should be also mentioned that this type of demand-side management procedures must handle concerns about privacy, security, and communication failures. For this reason, the energy management of EVs is also an open research topic. In another vein, flexible voltage and power flow control devices can be placed at strategic locations in distribution grids to optimize the operation of the distribution facilities.

The massive integration of renewable energies in power systems and the electrification of the transport sector and other energetic processes are the main challenges that power system operators and planners must face in the incoming years. It should not be forgotten that, despite of the technical complexities associated with the generation, transmission, and distribution of electricity, power systems can be considered so far as an example of a reliable and secure system with high quality standards. The average interruption time of power systems is almost null in most developed countries and the cost of the power supply for consumers is comparatively lower than other energy types. Therefore, the good performance of power systems should not be deteriorated as a consequence of the challenges that have been described above. Consequently, power system operators and planners must anticipate the changes that power systems are about to experience with the objective of maintaining the quality of the service. Fortunately, there are several tools that are available and can be used to ease the expected transformation of power systems. First, new electricity storage technologies are expected to play a relevant role in future power systems. Specially, electrochemical batteries are experiencing a technological revolution that make them suitable for providing different services as energy arbitrage, and local and grid support. Note that, so far, only hydro pumping units have been used to storage high amounts of energy. However, this type of facilities requires a specific location and resources that do not exist in all power systems. On the other hand, electrochemical batteries have a modular structure that make them suitable to be installed in any location of the system in a wide range of sizes. The usage of new net-zero emission fuels, as hydrogen, is also promising. Hydrogen is a fuel that may be burnt in gas turbines, as natural gas, to produce power without the emission of CO_2. The problem of obtaining hydrogen is that it requires the usage of electricity.

Electrolyzers are the devices used to obtain hydrogen from water and they require significant amounts of power. Then, hydrogen power plants may be of high interest in renewable dominated power systems. Renewable power surpluses can be used to produce hydrogen using electrolyzers, and hydrogen power plants can be used to produce electricity when renewable power is not available. The key factors for the future development of hydrogen-based power plants are to reduce the capital costs of electrolyzers, as well as to increase their efficiency and lifetime, and develop economical hydrogen storage units. The increasing participation of consumers in the operation of power systems is also another tool that can be used to facilitate the operation of power systems. So far, only large consumers have traditionally participated in the provision of specific services, as voluntary demand shed, or directly in the electricity markets. However, small-size consumers are expected to participate in demand-side management programs to modify their consumption patterns according to the needs of the operation of the system. In this manner, indirect or direct control procedures may be implemented to modify consumption profiles in exchange for a economical compensation. The services that power electronics can offer are also very interesting for the technical and economical operation of power systems. It is well known that Flexible AC Transmission Systems (FACTS) are able to improve significantly the performance of the transmission system. In this sense, the optimal operation of transmission lines and voltage control will be key in future power systems, where it is expected that some specific transmission lines be subject to a higher operation level. Finally, power system operators and planners have also available sophisticated mathematical-based decision-making tools and higher computational resources that will allow them to make informed decisions in this uncertain framework. Big data and decision-making under uncertainty models are examples of mathematical tools that can be used to operate and design future power systems.

As a conclusion, it can be stated that there is still a lot of work to be done to overcome the great challenges that power systems must face during next years. However, the power system community is working hard to develop new models, procedures, and devices that will allow us to increase the reliability, security, and quality of future power systems.

1.2 Renewable Energies

Renewable energies have significantly increased their presence in electric energy systems around the world because of their numerous advantages with respect to fossil-fuel and conventional generating technologies. Wind, solar, hydraulic, biomass, or geothermal energy, among others, represent natural endless resources available around the planet. This implies, firstly, a solution to generate electricity with a much lower carbon footprint than fossil fuel technologies [21]; secondly, the possibility of generating electricity independently of the willingness of third parties to supply fossil fuels or other scarce resources; thirdly, a distributed and local generation system

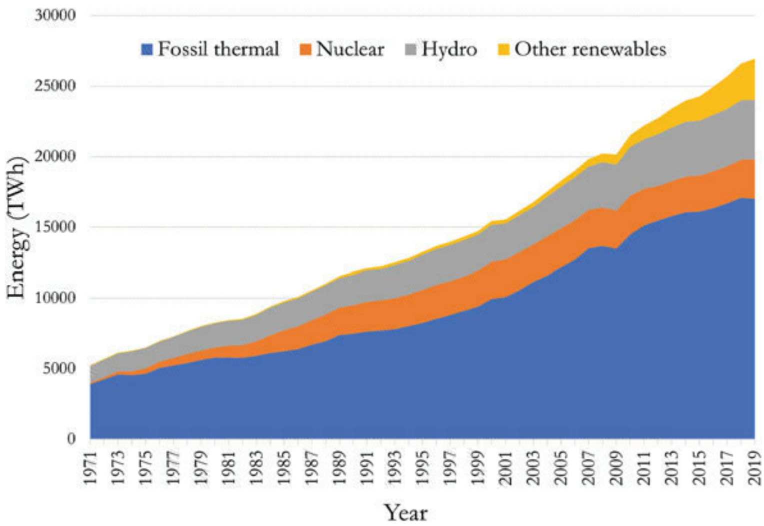

Fig. 1.1 World electricity generation by sources from 1971 to 2019

against a centralized and concentrated system; and fourthly, the growth of the local economy and the possibility of becoming autonomous in terms of energy supply.

The problem of climate change caused by anthropogenic GHG emissions has impulsed the use of renewable sources for electricity generation. According to the International Energy Agency (IEA) [12], the new capacity built in 2019 based on solar PV and wind power was 108 and 60 GW, respectively, and the forecast is a growth of 4% in the net new renewable capacity built in 2020. It is expected a global share of renewable sources in electricity generation of 27% in 2020. As it can be observed in Fig. 1.1, the electricity generation from renewable sources has grown 2.5 times from 2010 to 2019 [11]. Still, it is evident that a long way remains to effectively reduce the fossil-fuel dependency of this sector.

The main drawback of renewable sources such as wind or solar radiation is their lack of dispatchability. It is not possible to store these resources and it is difficult to predict their availability with an acceptable precision until a few hours in advance. This complicates the operation of a traditional power system where most of the energy and reserve capacity is scheduled at least one day prior to the energy delivery. Therefore, modifications in the market structures have been implemented in the last years to ease the integration of intermittent renewable electricity generation. In the European electricity market, for instance, the integration of the continuous and auction-based intraday markets is taken place among the countries inside the coordinated market [8]. Intraday markets happening along the delivery day allow a better adjustment of the intermittent generation to the actual renewable source availability, which entails a reduction in the ancillary service costs.

The technology of onshore wind and solar PV has reached the maturity level and their investment costs can nowadays compete with those of conventional technologies, such as combined-cycle gas turbines or coal units [13]. The technological development of other technologies, such as offshore wind, concentrated solar power, bioenergy, or ocean energy, is taking place and it is expected that as long as the effects of climate change become more severe in Western countries, the improvement of those technologies will be more promoted by governments and private investors. Finally, it is worth mentioning that nuclear power represents the main competitor to renewable energies since no GHGs are emitted in the electricity generation process. The technological evolution of emergent renewable technologies may be compromised if governments decide to bet for the nuclear power to mitigate the climate change effects.

In this book, we tackle different problems related with the integration and the impact of intermittent renewable generation in conventional power systems. In particular, Sect. 2.3 of Chap. 2 explains how to model the power production by renewable units using wind and solar PV sources. Related with the system operation, Chap. 4 focuses on solving a day-ahead scheduling problem with high intermittent renewable capacity, while Chap. 5 includes the presence of EVs. The modeling of the short-term uncertainties is specially crucial in these type of problems to obtain technically and economically feasible solutions. The other important problem related with renewable energies is the long-term planning. Therefore, Chaps. 8–12 are devoted to solve different planning situations. Specifically, Chaps. 8–9 study the single-stage and multi-stage capacity expansion problems in renewable capacity considering different uncertainty sources and modeling approaches.

1.3 Electric Vehicles

EVs are expected to play an important role in electric energy systems since their penetration is foreseen to significantly increase in the near future. This increase is mainly motivated by the fact that EVs can facilitate the reduction of CO_2 and other GHG emissions, especially in renewable-dominated power systems [15]. Moreover, the maturity of the technologies used for EVs makes them available for long-distance trips, which makes EVs more attractive for consumers.

Despite of the above possible benefits, a high penetration of EVs may have a great impact on the planning and operation of electric energy systems. Most EV users have similar driving patterns, arriving and departing from home and work at similar times. Therefore, if all users charge their EVs at the same time, this would translate into an increase in the peak demand in the system, which may make it necessary to build new generation and/or transmission facilities [5].

Nevertheless, EVs are parked and, thus, available for charging, most of the time. It is not necessary to charge them as soon as they are parked; instead the charging can be shifted to a more suitable time, e.g., to those hours with low prices, with low demand, or with high renewable power availability. This would result in a reduction of the charging costs or a reduction in the peak demand.

Another relevant aspect of EVs is that their batteries may be also used to inject energy into the network, i.e., the charging of EVs can be bidirectional, also known as vehicle-to-grid (V2G). In such a case, EVs can be seen as mobile energy storage units, which would increase the flexibility of power systems.

However, managing individual EVs has two main problems. On the one hand, an individual EV has limited flexibility since the owner may not be willing to change the timing of the charging unless it receives an incentive to do that. On the other hand, the high computation effort that would be needed to manage the charging and/or discharging of a high number of EVs. To deal with these two issues, the figure of an aggregator, which can be seen as an energy management system in charge of an EV fleet, is generally considered in the technical literature [14, 26]. The aggregator manages the charging of these EVs with the aim of minimizing the charging costs and guaranteeing that the driving requirements of EV users are satisfied.

Within this context, this book addresses some of the most relevant problems in electric energy systems with a high penetration of EVs. Firstly, Sect. 2.4 of Chap. 2 describes how to model the working of EVs in decision-making problems in power systems. Secondly, Chaps. 5–7 analyze operation problems with EVs, including the day-ahead market scheduling in Chap. 5, the bidding strategy of an EV aggregator in Chap. 6, and the pricing strategy of an electricity supplier for EVs in Chap. 7. Finally, Chaps. 8–12 deal with planning problems in power systems with EVs, including the generation expansion planning problem in Chaps. 8–10 and the transmission and distribution expansion planning problems in Chaps. 11 and 12, respectively.

1.4 Uncertainty

Decision-making problems in power systems are generally solved within an uncertain environment. For example, a power producer deciding its self-scheduling decisions for the next day faces the uncertainty in the market power prices, which are unknown at that time. Similarly, the owner of a renewable generating unit does not know in advance the available production levels since these depend on a meteorological phenomena such as the solar radiation or wind speed. Lastly, if an expansion planning problem is considered, the entity in charge of making these decisions, such as the building of new transmission lines or new generating units, must anticipate the power system conditions in the future, which is a difficult task since it involves forecasting the future demand or the future number of EVs in the system.

In order to obtain informed decisions, it becomes relevant to model these uncertainties in the decision-making problems. For this purpose, two relevant methods are generally considered in the technical literature and also addressed in this book, namely, scenario-based stochastic programming [3] and robust optimization [2].

Scenario-based stochastic programming models uncertain parameters through a set of scenarios. These scenarios characterize the possible realizations of uncertain parameters and each one has an associated probability of occurrence. In general, scenario-based stochastic programming problems can be classified into two-stage and multi-stage stochastic programming problems.

Two-stage stochastic programming models are used to represent decisions in two stages, namely, before and after knowing the uncertainty realization. The decision sequence in two-stage stochastic programming problems is as follows. Firstly, the decision-maker takes a decision before knowing the actual realization of the uncertain parameters. These decisions, which are also known as first-stage or here-and-now decisions, are independent on the future scenario realization. Secondly, the decision-maker is informed or gets information about the actual realization of the uncertain parameters. Finally, the decision-maker takes some corrective actions after knowing the actual uncertainty realization. These decisions, also known as second-stage or wait-and-see decisions, do depend on the scenario realization.

Multi-stage stochastic programming models are similar to two-stage stochastic programming problems but the decision sequence is repeated several times.

A key issue of scenario-based stochastic programming is an appropriate generation of scenarios, which must accurately represent the uncertain parameters. For this, it is key to have information about the probability distribution function of these parameters, which may be not available to the decision maker in some situations. Moreover, it is generally needed to consider a large enough number of scenarios in order to have a good representation of the uncertainty, which may translate into an intractable problem, mainly in complex decision-making problems. Even if the problem can be solved, it may involve a high computation time, which may not be acceptable for practical applications that need decisions to be made in a short time. Therefore, it is generally needed to achieve a trade-off between modeling accuracy and problem tractability when stochastic programming is considered to model decision-making problems under uncertainty.

On the other hand, robust optimization can be also used to model decision-making problems under uncertainty in power systems [25]. The main difference with scenario-based stochastic programming is that robust optimization guarantees the feasibility and optimality of the decisions provided that the uncertain parameters take values within a pre-specified uncertainty set, while scenario-based stochastic programming only guarantees the feasibility of the solution for the considered scenarios. This means that if the actual uncertainty realization is different to one of the scenarios considered, the solution may be infeasible.

Uncertainty sets for robust optimization are generally based on confidence bounds, which are usually easier to define even if the probability distribution function of the uncertain parameters is unknown. As a disadvantage of robust optimization, it can be mentioned that solutions may be too conservative.

Robust optimization problems can be also classified into static and dynamic problems, depending on the sequence of decisions. In a static robust optimization framework, decisions are made by anticipating that, once made, the worst-case uncertainty realization will occur. Within a dynamic robust optimization framework, after the uncertainty realization occurs, it is possible to apply some corrective actions, which provides the decision maker with additional flexibility.

Further information about stochastic programming and robust optimization models can be found in Sects. 3.2 and 3.3 of Chap. 3 of this book, respectively. Moreover, stochastic programming and robust optimization are used in this book to model decision making-problems under uncertainty, including operation problems in Chaps. 4–7 and planning problems in Chaps. 8–12.

1.5 Decision Making and Decision Framework. Motivating Examples

The main objective of this book is to provide scheduling and planning tools for power system operators and planners considering the presence of renewable energies and EVs. Different decision frameworks are considered depending on the characteristics of the particular problem to solve. Then, we can find throughout this book from day-ahead scheduling procedures to multi-year planning tools, spanning from short-term to long-term planning horizons.

The main decision-making problems analyzed in this book are summarized below.

1.5.1 Day-Ahead Market Scheduling Considering Renewable Energies

We consider a power system operator that aims at developing a day-ahead scheduling model to co-optimize energy and reserve capacity. The appropriate scheduling of energy and reserve becomes particularly important in power systems with high presence of renewable and intermittent power sources. This model can be formulated as a two-stage mixed-integer stochastic programming problem, where the first stage represents the day-ahead market and the second stage the balancing market. This problem is analyzed and formulated in Chap. 4. The uncertainty related to the demand, as well as to the wind and solar power is modeled. The decision framework of this problem is represented in Fig. 1.2.

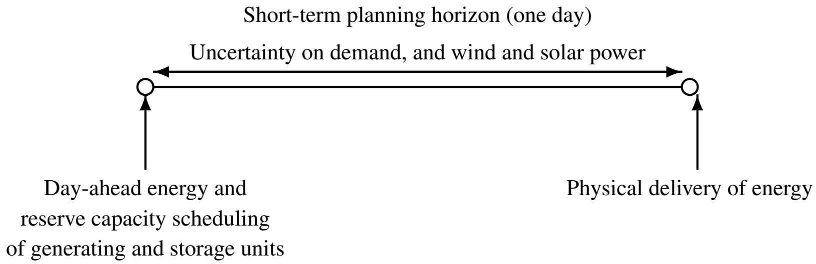

Fig. 1.2 Decision framework of the day-ahead market scheduling considering renewable energies